

The Fourth Generation Quark and the 750 GeV Diphoton Excess

Yu-Jie Zhang^{1,2,*}, Bin-Bin Zhou¹, and Jia-Jia Sun¹

¹ Key Laboratory of Micro-nano Measurement-Manipulation and Physics (Ministry of Education) and School of Physics, Beihang University, Beijing 100191, China

² CAS Center for Excellence in Particle Physics, Beijing 100049, China

(Dated: February 18, 2016)

Recently, the CMS and ATLAS collaborations have reported a diphoton peak at 750 GeV in the RunII of LHC at 13 TeV. We assume that the heavy fourth generation quark doublet z, y with 380 GeV mass, and the width of z, t is much less b quark. Then we show that the contributions of the $(z\bar{z} + y\bar{y})/\sqrt{2}$ bound state $\eta_{zy}(1S)$ to the diphoton measurements through $\sigma(pp \rightarrow \eta_{zy}(1s) \rightarrow \gamma\gamma)$ are $5.6^{+5.6}_{-2.8}$ fb at $\sqrt{s} = 13$ TeV. They are constant with the 750 GeV diphoton excess measured by the CMS and ATLAS collaborations.

PACS numbers: 12.60.-i, 14.80.-j, 14.40.Pq

Keywords: Phenomenology of models beyond the standard model, Hadronic Colliders, Heavy quarkonia

INTRODUCTION

Recently, the CMS and ATLAS collaborations have reported a diphoton excess at 750 GeV with width 45 GeV in the RunII of LHC at 13 TeV:

$$\sigma(pp \rightarrow \gamma\gamma) \approx \begin{cases} (6 \pm 3) \text{ fb} & \text{CMS [1]} \\ (10 \pm 3) \text{ fb} & \text{ATLAS [2].} \end{cases} \quad (1)$$

A lot of studies have been done here [3–46]. We study the possibility that it is a bound states of the fourth generation quark and anti-quark here. The fourth generation quarks and leptons were proposed about 30 years ago [47]. In another hand, the branching fraction $Br(H \rightarrow \tau\mu) = (0.84^{+0.39}_{-0.37})\%$ measured by CMS collaboration [48] may be indicate the fourth generation neutrino here.

In this letter, we assume that, the heavy fourth generate quark z, y with 380 GeV mass and charge $e_z = 2/3$, $e_y = -1/3$, and the modified CKM matrix elements $|V_{zq}| \sim |V_{yq'}| \ll 1$ for $q = d, s, b$ and $q' = u, c, t$. Then the width of z, y quark is much less b quark, it will form the bound state such as $z\bar{u}$ or $z\bar{d}$, which is long life particle and do not decay in the detector. Then the bound state $(z\bar{z} + y\bar{y})/\sqrt{2}$ quarkonium states $\eta_{zy}(1S)$ will be first particle with fourth generation quark component which may be measured at LHC. The fourth generation quark had been searched by the CMS collaboration at $\sqrt{s} = 8$ TeV, and the lower limit lies between 687 and 782 GeV for all possible values of the branching fractions into the three different final states assuming strong production [49]. So we require the width of z, y quark is much less b quark and it will not decay in the detectors. The bound states of fourth generate quark have been studied in Ref. [50–52] In the next section, the decay of $\eta_{zy}(1s)$ is presented, and the production is followed. Finally, a summary is given.

DECAY

First, we study the decay mode of $\eta_{zy}(1s)$ states. The diphoton and digluon decay widths have been studied to

higher order [53–56], and the leading order (LO) results are given here,

$$\begin{aligned} \Gamma(\eta_{zy} \rightarrow gg) &= \frac{16\alpha_s(m_z)^2 |R_s(0)|^2}{3m_{\eta_{zy}}^2}, \\ \Gamma(\eta_{zy} \rightarrow \gamma\gamma) &= \frac{6\alpha(m_z)^2 (e_z^2 + e_y^2) |R_s(0)|^2}{m_{\eta_{zy}}^2} \\ &= \frac{50\alpha(m_z)^2 |R_s(0)|^2}{27m_{\eta_{zy}}^2}, \\ \frac{\Gamma(\eta_{zy} \rightarrow gg)}{\Gamma(\eta_{zy} \rightarrow \gamma\gamma)} &= \frac{72\alpha_s(m_z)^2}{25\alpha(m_z)^2} \sim 4 \times 10^2, \end{aligned} \quad (2)$$

where the $|R_s(0)|$ is the radial wave functions of η_{zy} at origin. And the width of electroweak decay mode of pure η_{zy} can be given as,

$$\begin{aligned} \Gamma(\eta_{zy} \rightarrow HH) &= \Gamma(\eta_{zy} \rightarrow H\gamma) = 0, \\ \frac{\Gamma(\eta_{zy} \rightarrow f\bar{f})}{\Gamma(\eta_{zy} \rightarrow \gamma\gamma)} &= 0, \\ \frac{\Gamma(\eta_{zy} \rightarrow W^+W^-)}{\Gamma(\eta_{zy} \rightarrow \gamma\gamma)} &\sim 2, \\ \frac{\Gamma(\eta_{zy} \rightarrow ZZ)}{\Gamma(\eta_{zy} \rightarrow \gamma\gamma)} &\sim 3, \\ \frac{\Gamma(\eta_{zy} \rightarrow Z\gamma)}{\Gamma(\eta_{zy} \rightarrow \gamma\gamma)} &\sim 0.5. \end{aligned} \quad (3)$$

We ignore the $\mathcal{O}(m_H^2/m_z^2)$, $\mathcal{O}(m_Z^2/m_z^2)$, $\mathcal{O}(m_W^2/m_z^2)$, and $\mathcal{O}(m_f^2/m_z^2)$ here. The HZ and $t\bar{t}$ widths of η_z are enhance by m_z^4/m_Z^4 and $m_z^2 m_t^2/m_Z^4$ respectively,

$$\begin{aligned} \frac{\Gamma(\eta_z \rightarrow HZ)}{\Gamma(\eta_z \rightarrow \gamma\gamma)} &= \frac{81m_z^4}{256C_w^2 S_w^2 m_Z^4} \sim 3 \times 10^3, \\ \frac{\Gamma(\eta_z \rightarrow t\bar{t})}{\Gamma(\eta_z \rightarrow \gamma\gamma)} &= \frac{243m_z^2 m_t^2}{512C_w^2 S_w^2 m_Z^4} \sim 1 \times 10^3. \end{aligned} \quad (4)$$

The HZ decay model of η_z is dominant, which is consistent with Ref. [50]. But if we consider the electroweak decay mode of $\eta_{zy}(\frac{z\bar{z}+y\bar{y}}{\sqrt{2}})$, we can get $\Gamma(\eta_{zy} \rightarrow f\bar{f}) = \Gamma(\eta_{zy} \rightarrow$

$HZ) = 0$, which is canceled between $z\bar{z}$ and $y\bar{y}$. The ratios of $\frac{\Gamma(\eta_z \rightarrow VV)}{\Gamma(\eta_z \rightarrow \gamma\gamma)}$ are given here,

$$\begin{aligned}\frac{\Gamma(\eta_z \rightarrow W^+ W^-)}{\Gamma(\eta_z \rightarrow \gamma\gamma)} &\sim \frac{81}{128S_w^4(1+m_y^2/m_z^2)^2} \sim 3, \\ \frac{\Gamma(\eta_z \rightarrow ZZ)}{\Gamma(\eta_z \rightarrow \gamma\gamma)} &\sim \frac{(32S_w^2 - 24S_w^2 + 9)^2}{1024C_w^4 S_w^4} \sim 0.8, \\ \frac{\Gamma(\eta_z \rightarrow Z\gamma)}{\Gamma(\eta_z \rightarrow \gamma\gamma)} &\sim \frac{(8S_w^2 - 3)^2}{32C_w^2 S_w^2} \sim 0.2.\end{aligned}\quad (5)$$

The electroweak decay width is much less than the strong decay width, and $\Gamma_{tot}(\eta_{zy}(1s)) \sim \Gamma(\eta_{zy}(1s) \rightarrow gg)$.

The radial wave functions at origin $|R_s(0)|$ can be given through the Schrodinger equation with static potential. The gluon exchange potential had been calculated to two loop result [57–59], three loop [60, 61]. We use one loop potential for $S = 0$ states [62, 63] here, where the $\mathcal{O}(\frac{\alpha_s^2}{m_z})$ potential is included [64–69]

$$\begin{aligned}V_{gluon}(r) &= -\frac{4\alpha_s}{3r} - \frac{\alpha_s^2}{3\pi r} \left(\frac{31}{3} - \frac{10}{9}n_f \right) - \frac{2\alpha_s^2}{m_z r^2} \\ &\quad - \frac{4\pi\alpha_s^2}{3m_z^2} \delta(\vec{r}) + \frac{2\alpha_s}{3m_z^2 r} \left[\vec{\nabla}^2 + \frac{1}{r^2} \vec{r}(\vec{r} \cdot \vec{\nabla}) \vec{r} \right],\end{aligned}$$

where $n_f = 5$ is the number of light-quark flavors. The photon exchange potential is

$$V_{photon}(r) = -\frac{5}{18} \frac{\alpha}{r}, \quad (6)$$

The Higgs exchange potential had been calculated to one loop, where the large fermion mass is canceled out and hence produces no enhancement for the radiative corrections [70, 71]. So that the Higgs exchange potential in the momentum space is given as [51, 72]:

$$V_{Higgs}(r) = -\frac{g_z^2 e^{-m_H r}}{4\pi r} \left(1 + \frac{m_z^2}{2\pi^2 v^2} + \frac{7m_t^2}{16\pi^2 v^2} \right), \quad (7)$$

where $g_z = \frac{m_z}{v}$, $\frac{g_z^2}{4\pi} \sim 0.2$, $v = 246$ GeV, and $m_H = 125$ GeV.

The relativistic corrections of kinetic energy and Higgs exchange potential and the contributions of ghost of W , Z are [51]

$$\begin{aligned}V_{rel}(r) &= -\frac{(\vec{\nabla}^2)^2}{4m_z^3} - \frac{1}{2v^2} \delta(\vec{r}) \\ &\quad + \frac{m_H^2 e^{-m_H r} - m_Z^2 e^{-m_Z r} + 2m_W^2 e^{-m_W r}}{16\pi v^2 r}.\end{aligned}\quad (8)$$

The first term are the relativistic corrections of kinetic energy. The total potential is

$$V(r) = V_{gluon}(r) + V_{photon}(r) + V_{Higgs}(r) + V_{rel}(r) \quad (9)$$

In the numerical calculation, the strong coupling constant can be determined through $\alpha_s(m_z v_z/2) \sim v_z$ in the

non-relativistic bound states[53], then $\alpha_s \sim 0.162$. The variational method is used here, and the test function is select as the hydrogen atom radial wave functions

$$R_{1s}(r) = 2 \times q^{3/2} \times e^{-qr}. \quad (10)$$

Then we get the radial wave functions of $\eta_{zy}(1s)$ is

$$\begin{aligned}q &= 98 \text{ GeV} \\ \frac{|R_{1s}(0)|^2}{m_{\eta_{zy}}^2} &= 6.9 \text{ GeV}^3.\end{aligned}\quad (11)$$

If we consider the LO Coulomb potential only, $\frac{|R_{1s}(0)|^2}{m_{\eta_{zy}}^2} \sim 0.1$ GeV, which is consistent with the result in [50]. If we consider the LO Coulomb and higgs exchange potential only, our result is consistent with the result in [50, 52]. The other potential terms absorb the wavefunction to the origin and enhance q in Eq.(10).

In another hand, $\alpha_s(m_z) \sim 0.092$, $\alpha(m_z) \sim 1/120$. We can get the properties of $\eta_{zy}(1s)$ states [53],

$$\begin{aligned}E_1 &= -10 \text{ GeV}, \\ M_{\eta_{zy}(1s)} &= 2m_z + E_1 = 750 \text{ GeV}, \\ \Gamma(\eta_{zy}(1s) \rightarrow gg) &= 0.30 \text{ GeV}, \\ \Gamma(\eta_{zy}(1s) \rightarrow \gamma\gamma) &= 0.86 \text{ MeV}, \\ Br(\eta_{zy}(1s) \rightarrow \gamma\gamma) &= 2.8 \times 10^{-3}.\end{aligned}\quad (12)$$

PRODUCTION

The leading order (LO) parton cross section of $\eta_{zy}(1s)$ can be get through [73]:

$$\hat{\sigma}_{LO}(gg \rightarrow \eta_{zy}(1s)) = \sigma_0 M_{\eta_{zy}(1s)}^2 \delta(\hat{s} - M_{\eta_{zy}(1s)}^2) \quad (13)$$

and

$$\sigma_0 = \frac{\pi^2}{8M_{\eta_{zy}(1s)}^3} \Gamma_{LO}(\eta_{zy}(1s) \rightarrow gg) \quad (14)$$

where \hat{s} is the invariant energy squared of initial states gg . And the hadronic cross section of $\eta_{zy}(1s)$ is

$$\begin{aligned}\sigma_{LO}(pp \rightarrow \eta_{zy}(1s)) &= \sigma_0 \tau \int_{\tau}^1 \frac{dx}{x} f(x) f\left(\frac{\tau}{x}\right) \\ &= \frac{\Gamma_{LO}(\eta_{zy}(1s) \rightarrow gg) \pi^2}{M_{\eta_{zy}(1s)} S} \frac{1}{8} \int_{\tau}^1 \frac{dx}{x} f(x) f\left(\frac{\tau}{x}\right),\end{aligned}\quad (15)$$

where $\tau = M_{\eta_{zy}(1s)}^2/S$, and S is the invariant mass square of initial proton-proton. Then its contribution to the diphoton distribution is

$$\begin{aligned}\sigma_{LO}(pp \rightarrow \eta_{zy}(1s) \rightarrow \gamma\gamma) &= \frac{\Gamma_{LO}(\eta_{zy}(1s) \rightarrow \gamma\gamma) \pi^2}{M_{\eta_{zy}(1s)} S} \frac{1}{8} \int_{\tau}^1 \frac{dx}{x} f(x) f\left(\frac{\tau}{x}\right),\end{aligned}\quad (16)$$

Then $\frac{\pi^2}{8} \int_{\tau}^1 \frac{dx}{x} f(x) f(\frac{\tau}{x})$ is 2137 for $\sqrt{s} = 13$ TeV [3, 46]. Then we can get the cross sections at $\sqrt{s} = 13$ TeV,

$$\sigma(pp \rightarrow \eta_{zy}(1s) \rightarrow \gamma\gamma) = 5.6_{-2.8}^{+5.6} \text{ fb.} \quad (17)$$

The relative error bar is estimated as $1_{-0.5}^{+1.0}$ from the α_s , factorization scale, higher order corrections, and so on. The higher states $\eta_{zy}(n s)$ for $n = 2, 3, \dots$ will contribute to the diphoton distribution, which may enlarge the measured width of the diphoton excess.

SUMMARY

In summary, we assume that the heavy fourth generation quark doublet z, y with 380 GeV mass, and the width of z, t is much less b quark. Then we show that the contributions of the $(z\bar{z} + y\bar{y})/\sqrt{2}$ bound state $\eta_{zy}(1s)$ to the diphoton measurements through $\sigma(pp \rightarrow \eta_{zy}(1s) \rightarrow \gamma\gamma)$ are $5.6_{-2.8}^{+5.6}$ fb at $\sqrt{s} = 13$ TeV. They are constant with the 750 GeV diphoton excess measured by the CMS and ATLAS collaborations.

We would like to thank K.T. Chao, B.Q. Li for useful discussions. This work is supported by the National Natural Science Foundation of China (Grants No. 11375021, 11575017), the New Century Excellent Talents in University (NCET) under grant NCET-13-0030, the Major State Basic Research Development Program of China (No. 2015CB856701), and the Fundamental Research Funds for the Central Universities.

* Electronic address: nophy0@gmail.com

- [1] **CMS** Collaboration, C. Collaboration, *Search for new physics in high mass diphoton events in proton-proton collisions at 13 TeV*, CMS-PAS-EXO-15-004.
- [2] **ATLAS** Collaboration, T. A. collaboration, *Search for resonances decaying to photon pairs in 3.2 fb⁻¹ of pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, ATLAS-CONF-2015-081.
- [3] R. Franceschini, G. F. Giudice, J. F. Kamenik, M. McCullough, A. Pomarol, R. Rattazzi, M. Redi, F. Riva, A. Strumia, and R. Torre, *What is the gamma gamma resonance at 750 GeV?*, arXiv:1512.04933.
- [4] Q.-H. Cao, Y. Liu, K.-P. Xie, B. Yan, and D.-M. Zhang, *A Boost Test of Anomalous Diphoton Resonance at the LHC*, arXiv:1512.05542.
- [5] L. Bian, N. Chen, D. Liu, and J. Shu, *A hidden confining world on the 750 GeV diphoton excess*, arXiv:1512.05759.
- [6] D. Curtin and C. B. Verhaaren, *Quirky Explanations for the Diphoton Excess*, arXiv:1512.05753.
- [7] S. Fichtel, G. von Gersdorff, and C. Royn, *Scattering Light by Light at 750 GeV at the LHC*, arXiv:1512.05751.
- [8] W. Chao, R. Huo, and J.-H. Yu, *The Minimal Scalar-Stealth Top Interpretation of the Diphoton Excess*, arXiv:1512.05738.
- [9] S. V. Demidov and D. S. Gorbunov, *On sgoldstino interpretation of the diphoton excess*, arXiv:1512.05723.
- [10] J. M. No, V. Sanz, and J. Setford, *See-Saw Composite Higgses at the LHC: Linking Naturalness to the 750 GeV Di-Photon Resonance*, arXiv:1512.05700.
- [11] D. Becirevic, E. Bertuzzo, O. Sumensari, and R. Z. Funchal, *Can the new resonance at LHC be a CP-Odd Higgs boson?*, arXiv:1512.05623.
- [12] P. Agrawal, J. Fan, B. Heidenreich, M. Reece, and M. Strassler, *Experimental Considerations Motivated by the Diphoton Excess at the LHC*, arXiv:1512.05775.
- [13] A. Ahmed, B. M. Dillon, B. Grzadkowski, J. F. Gunion, and Y. Jiang, *Higgs-radion interpretation of 750 GeV di-photon excess at the LHC*, arXiv:1512.05771.
- [14] P. Cox, A. D. Medina, T. S. Ray, and A. Spray, *Diphoton Excess at 750 GeV from a Radion in the Bulk-Higgs Scenario*, arXiv:1512.05618.
- [15] A. Kobakhidze, F. Wang, L. Wu, J. M. Yang, and M. Zhang, *LHC diphoton excess explained as a heavy scalar in top-seesaw model*, arXiv:1512.05585.
- [16] B. Dutta, Y. Gao, T. Ghosh, I. Gogoladze, and T. Li, *Interpretation of the diphoton excess at CMS and ATLAS*, arXiv:1512.05439.
- [17] C. Petersson and R. Torre, *The 750 GeV diphoton excess from the goldstino superpartner*, arXiv:1512.05333.
- [18] M. Low, A. Tesi, and L.-T. Wang, *A pseudoscalar decaying to photon pairs in the early LHC run 2 data*, arXiv:1512.05328.
- [19] S. D. McDermott, P. Meade, and H. Ramani, *Singlet Scalar Resonances and the Diphoton Excess*, arXiv:1512.05326.
- [20] E. Molinaro, F. Sannino, and N. Vignaroli, *Strong dynamics or axion origin of the diphoton excess*, arXiv:1512.05334.
- [21] R. S. Gupta, S. Jäger, Y. Kats, G. Perez, and E. Stamou, *Interpreting a 750 GeV Diphoton Resonance*, arXiv:1512.05332.
- [22] J. Ellis, S. A. R. Ellis, J. Quevillon, V. Sanz, and T. You, *On the Interpretation of a Possible ~ 750 GeV Particle Decaying into $\gamma\gamma$* , arXiv:1512.05327.
- [23] X.-J. Huang, W.-H. Zhang, and Y.-F. Zhou, *A 750 GeV dark matter messenger at the Galactic Center*, arXiv:1512.08992.
- [24] X.-J. Bi, R. Ding, Y. Fan, L. Huang, C. Li, T. Li, S. Raza, X.-C. Wang, and B. Zhu, *A Promising Interpretation of Diphoton Resonance at 750 GeV*, arXiv:1512.08497.
- [25] W. Chao, *Neutrino Catalyzed Diphoton Excess*, arXiv:1512.08484.
- [26] C. Cai, Z.-H. Yu, and H.-H. Zhang, *The 750 GeV diphoton resonance as a singlet scalar in an extra dimensional model*, arXiv:1512.08440.
- [27] Y.-L. Tang and S.-h. Zhu, *NMSSM extended with vector-like particles and the diphoton excess on the LHC*, arXiv:1512.08323.
- [28] J. Cao, F. Wang, and Y. Zhang, *Interpreting The 750 GeV Diphoton Excess Within TopFlavor Seesaw Model*, arXiv:1512.08392.
- [29] G. Li, Y.-n. Mao, Y.-L. Tang, C. Zhang, Y. Zhou, and S.-h. Zhu, *A Loop-philic Pseudoscalar*, arXiv:1512.08255.
- [30] J. Gao, H. Zhang, and H. X. Zhu, *Diphoton excess at 750 GeV: gluon-gluon fusion or quark-antiquark annihilation?*, arXiv:1512.08478.
- [31] Q.-H. Cao, Y. Liu, K.-P. Xie, B. Yan, and D.-M. Zhang, *The Diphoton Excess, Low Energy Theorem and the 331 Model*, arXiv:1512.08441.
- [32] F. Wang, W. Wang, L. Wu, J. M. Yang, and M. Zhang, *Interpreting 750 GeV Diphoton Resonance in the NMSSM with Vector-like Particles*, arXiv:1512.08434.
- [33] H. An, C. Cheung, and Y. Zhang, *Broad Diphotons from Narrow States*, arXiv:1512.08378.
- [34] H. Han, S. Wang, and S. Zheng, *Dark Matter Theories in the Light of Diphoton Excess*, arXiv:1512.07992.
- [35] J. Liu, X.-P. Wang, and W. Xue, *LHC diphoton excess from*

- colorful resonances, arXiv:1512.07885.
- [36] J. Zhang and S. Zhou, *Electroweak Vacuum Stability and Diphoton Excess at 750 GeV*, arXiv:1512.07889.
- [37] X.-J. Bi, Q.-F. Xiang, P.-F. Yin, and Z.-H. Yu, *The 750 GeV diphoton excess at the LHC and dark matter constraints*, arXiv:1512.06787.
- [38] F. P. Huang, C. S. Li, Z. L. Liu, and Y. Wang, *750 GeV Diphoton Excess from Cascade Decay*, arXiv:1512.06732.
- [39] F. Wang, L. Wu, J. M. Yang, and M. Zhang, *750 GeV Diphoton Resonance, 125 GeV Higgs and Muon g-2 Anomaly in Deflected Anomaly Mediation SUSY Breaking Scenario*, arXiv:1512.06715.
- [40] J. Cao, C. Han, L. Shang, W. Su, J. M. Yang, and Y. Zhang, *Interpreting the 750 GeV diphoton excess by the singlet extension of the Manohar-Wise Model*, arXiv:1512.06728.
- [41] R. Ding, L. Huang, T. Li, and B. Zhu, *Interpreting 750 GeV Diphoton Excess with R-parity Violation Supersymmetry*, arXiv:1512.06560.
- [42] W. Chao, *Symmetries Behind the 750 GeV Diphoton Excess*, arXiv:1512.06297.
- [43] T.-F. Feng, X.-Q. Li, H.-B. Zhang, and S.-M. Zhao, *The LHC 750 GeV diphoton excess in supersymmetry with gauged baryon and lepton numbers*, arXiv:1512.06696.
- [44] H. Han, S. Wang, and S. Zheng, *Scalar Explanation of Diphoton Excess at LHC*, arXiv:1512.06562.
- [45] M.-x. Luo, K. Wang, T. Xu, L. Zhang, and G. Zhu, *Squarkonium/Diquarkonium and the Di-photon Excess*, arXiv:1512.06670.
- [46] W. Liao and H.-q. Zheng, *Scalar resonance at 750 GeV as composite of heavy vector-like fermions*, arXiv:1512.06741.
- [47] V. D. Barger, H. Baer, K. Hagiwara, and R. J. N. Phillips, *Fourth Generation Quarks and Leptons*, *Phys. Rev. D* **30** (1984) 947–960.
- [48] CMS Collaboration, V. Khachatryan et al., *Search for Lepton-Flavour-Violating Decays of the Higgs Boson*, *Phys. Lett. B* **749** (2015) 337–362, [arXiv:1502.07400].
- [49] CMS Collaboration, S. Chatrchyan et al., *Inclusive search for a vector-like T quark with charge $\frac{2}{3}$ in pp collisions at $\sqrt{s} = 8$ TeV*, *Phys. Lett. B* **729** (2014) 149–171, [arXiv:1311.7667].
- [50] K. Hagiwara, K. Kato, A. D. Martin, and C. K. Ng, *Properties of Heavy Quarkonia and Related States*, *Nucl. Phys. B* **344** (1990) 1–32.
- [51] K. Ishiwata and M. B. Wise, *Fourth Generation Bound States*, *Phys. Rev. D* **83** (2011) 074015, [arXiv:1103.0611].
- [52] S. Kim, *Nonrelativistic lattice study of stoponium*, *Phys. Rev. D* **92** (2015) 094505, [arXiv:1508.07080].
- [53] G. T. Bodwin, E. Braaten, and G. P. Lepage, *Rigorous QCD analysis of inclusive annihilation and production of heavy quarkonium*, *Phys. Rev. D* **51** (1995) 1125–1171, [hep-ph/9407339].
- [54] H.-K. Guo, Y.-Q. Ma, and K.-T. Chao, *$O(\alpha_s v^2)$ Corrections to Hadronic and Electromagnetic Decays of 1S_0 Heavy Quarkonium*, *Phys. Rev. D* **83** (2011) 114038, [arXiv:1104.3138].
- [55] J.-Z. Li, Y.-Q. Ma, and K.-T. Chao, *QCD and Relativistic $O(\alpha_s v^2)$ Corrections to Hadronic Decays of Spin-Singlet Heavy Quarkonia h_c, h_b and η_b* , *Phys. Rev. D* **88** (2013) 034002, [arXiv:1209.4011].
- [56] F. Feng, Y. Jia, and W.-L. Sang, *Can Nonrelativistic QCD Explain the $\gamma\gamma^* \rightarrow \eta_c$ Transition Form Factor Data?*, *Phys. Rev. Lett.* **115** (2015) 222001, [arXiv:1505.02665].
- [57] M. Peter, *The Static potential in QCD: A Full two loop calculation*, *Nucl. Phys. B* **501** (1997) 471–494, [hep-ph/9702245].
- [58] Y. Schroder, *The Static potential in QCD to two loops*, *Phys. Lett. B* **447** (1999) 321–326, [hep-ph/9812205].
- [59] B. A. Kniehl, A. A. Penin, Y. Schroder, V. A. Smirnov, and M. Steinhauser, *Two-loop static QCD potential for general colour state*, *Phys. Lett. B* **607** (2005) 96–100, [hep-ph/0412083].
- [60] M. Peter, *The Static quark - anti-quark potential in QCD to three loops*, *Phys. Rev. Lett.* **78** (1997) 602–605, [hep-ph/9610209].
- [61] M. Beneke, Y. Kiyo, and K. Schuller, *Third-order correction to top-quark pair production near threshold I. Effective theory set-up and matching coefficients*, arXiv:1312.4791.
- [62] S. N. Gupta and S. F. Radford, *Quark Quark and Quark - Anti-quark Potentials*, *Phys. Rev. D* **24** (1981) 2309–2323.
- [63] S. N. Gupta and S. F. Radford, *REMARKS ON QUARK QUARK AND QUARK - ANTI-QUARK POTENTIALS*, *Phys. Rev. D* **25** (1982) 3430–3432.
- [64] K. Melnikov and A. Yelkhovsky, *Top quark production at threshold with $O(\alpha_s^{**2})$ accuracy*, *Nucl. Phys. B* **528** (1998) 59–72, [hep-ph/9802379].
- [65] B. A. Kniehl, A. A. Penin, M. Steinhauser, and V. A. Smirnov, *NonAbelian $\alpha_s^{**3}(s) / (m(q))^{**2}$ heavy quark anti-quark potential*, *Phys. Rev. D* **65** (2002) 091503, [hep-ph/0106135].
- [66] A. V. Manohar and I. W. Stewart, *The QCD heavy quark potential to order v^{**2} : One loop matching conditions*, *Phys. Rev. D* **62** (2000) 074015, [hep-ph/0003032].
- [67] N. Brambilla, A. Pineda, J. Soto, and A. Vairo, *The QCD potential at $O(1/m)$* , *Phys. Rev. D* **63** (2001) 014023, [hep-ph/0002250].
- [68] A. H. Hoang and T. Teubner, *Top quark pair production at threshold: Complete next-to-next-to-leading order relativistic corrections*, *Phys. Rev. D* **58** (1998) 114023, [hep-ph/9801397].
- [69] M. Beneke, A. Signer, and V. A. Smirnov, *Top quark production near threshold and the top quark mass*, *Phys. Lett. B* **454** (1999) 137–146, [hep-ph/9903260].
- [70] M. Yu. Kuchiev, *Amplitudes of radiative corrections in fermion bags bound by Higgs boson exchange*, arXiv:1012.0903.
- [71] M. Yu. Kuchiev and V. V. Flambaum, *Radiative corrections in fermion bags bound by Higgs boson exchange*, *Europhys. Lett.* **97** (2012) 51001, [arXiv:1012.0902].
- [72] M. J. Strassler and M. E. Peskin, *The Heavy top quark threshold: QCD and the Higgs*, *Phys. Rev. D* **43** (1991) 1500–1514.
- [73] M. Spira, A. Djouadi, D. Graudenz, and P. M. Zerwas, *Higgs boson production at the LHC*, *Nucl. Phys. B* **453** (1995) 17–82, [hep-ph/9504378].